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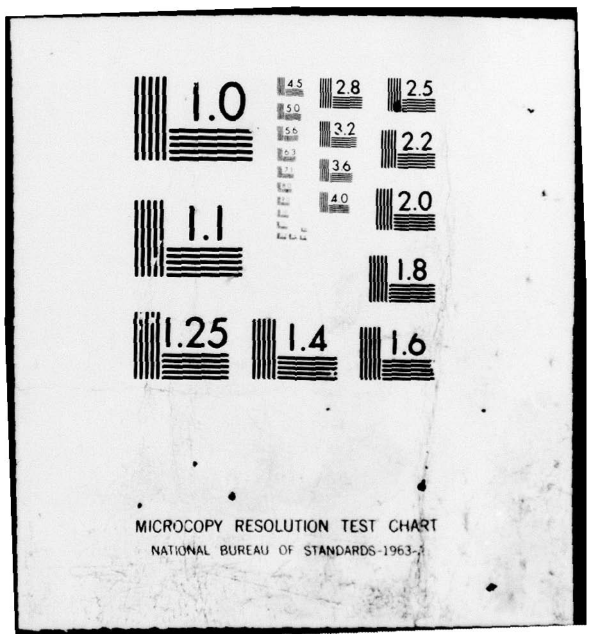
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The Transient Tokamak

W. M. Manheimer and N. K. Winsor

Plasma Theory Branch
Plasma Physics Division

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A tokamak plasma, and its toroidal current, can be generated by an intense pulsed ion beam. The beam is injected into a target plasma or empty vacuum chamber and then builds the plasma around it. It is shown that ignition is theoretically possible for a dense, high field tokamak.

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THE TRANSIENT TOKAMAK

Previous publications have examined heating of a tokamak plasma with an intense pulsed ion beam.[1,2] One advantage of this heating scheme as compared to most others is that such beams are quite efficient. For instance with reflex tetrodes, beams with voltage, current and pulse times of 1 Mev, 300 KA and 6×10^{-8} sec are produced with 40% efficiency.[3] There is a good reason to believe that all of these parameters, including the efficiency can be scaled up. Another advantage is the possible elimination of the Ohmic heating transformer and the resulting simplification of tokamak design.

The beam sets up a polarization field which E x B drifts the beam across the vacuum region to the plasma edge. The theory of this process has long been known,[4] and the basic requirement is $\omega_{pi}^2/\omega_{ci}^2 \gg 1$. Recently an initial experiment[5] has demonstrated that an ion beam with voltage V = 500 Kev and current $I = 5 \times 10^2$ Amps $\left(\frac{\omega_{pi}^2}{\omega_{ci}^2} = 30\right)$ propagates across a 10 KG Field with more than 50% efficiency. However it is not clear whether the polarization drift or other space charge effects are responsible for the transmission. An important consideration then is the means by which beam propagates across the plasma, (which is a good conductor and shorts out the polarization field), to deposit its energy in the center. Two mechanisms have so far been examined; first the beam energy can be so high as to exclude the tokamak field. The beam

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then displaces the plasma well into the interior of the discharge and deposits its energy where the Kelvin Helmholtz instability mixes the beam and plasma.[1] Second, a neoclassical process involves the beam ion banana orbits which pass near the center of the plasma.[2] As the ions travel back and forth from the plasma edge to the center, much of this energy is deposited near the center, since that is where the density is highest.

This letter explores another, and still more promising method of heating a tokamak plasma with an intense pulsed ion beam. With this method the ion beam is first injected nearly tangent to the field, and then the plasma column is built around it. There are two possible ways to do this, the details of which will be explored more fully in future publications. In the first method one produces a plasma only in the center of the tokamak, shoots the beam into this target plasma, and then when the beam is trapped in the center, builds the remaining plasma up around it by gas puffing.[6] The initial target plasma could be formed by electron cyclotron resonance breakdown or else by producing a low density, full volume plasma, and then utilizing either major or vertical field compression to move the plasma away from the outer wall. In this case, we find[6] that the initial target plasma must carry the full tokamak current. However once the beam is shot in, it maintains the current. Thus the power requirements on the poloidal field (Ohmic heating) transformer are drastically reduced.

The second approach is to shoot the ion beam into a vacuum or low density gas. The beam generates current and poloidal field, in

doing so it loses energy, and therefore becomes trapped in the torus. This method has been experimentally demonstarted in the analogous case of an intense pulsed electron beam injected into a torus.[7] In our case, the ion beam actually can provide the poloidal fields, so there is no need for a transformer or iron core at all. An analysis of this problem will be presented elsewhere.[8] It is important to note that relevant ion beam equilibria are known to exist in geometries with and without a conducting shell. Also the beams can be positioned by adjusting the vertical field.[9]

For either injection scheme, the key point is that ion beam energy can be injected only once, at the beginning of the discharge. Thus the plasma heats up and (if ignition is not attained) then decays. That is, it is transient in nature.

For high field high density plasmas, our calculations indicate that this single pulse of ion beam energy (about 1 megajoule) is sufficient to reach ignition. For larger volume, lower field devices, it is able to heat the plasma to thermonuclear temperatures and produce $Q \sim 0.1$. However, our calculations indicate that additional ion heating is needed for breakeven. An important advantage of the transient tokamak is that small, but scaleable experiments can be performed in either linear or toroidal geometry.

To examine the various processes involved in tokamak heating with intense pulsed beams, we have numerically solved a system of differential equations for beam velocity, electron and ion temperature and poloidal field. They are

$$\frac{dV_b}{dt} = -\nu_{be}(V_b - V_e) - \nu_{bi}V_b + \frac{eE}{M_b} \tag{1}$$

$$\frac{3}{2} n_e \frac{dT_e}{dt} = n_b M_b \nu_{be} (V_b - V_e)V_b - E\, n_e eV_e - n_e \nu_{eq}(T_e - T_i)$$

$$- \frac{3}{2} \frac{n_e T_e}{\tau_e} + P_\alpha - P_r \tag{2}$$

$$\frac{3}{2} n_i \frac{dT_i}{dt} = n_e \nu_{eq}(T_e - T_i) + n_b M_b \nu_{bi} V_b{}^2 - \frac{3}{2} \frac{n_i T_i}{\tau_i} \tag{3}$$

$$\frac{d}{dt}\left(\frac{1}{2} + 2\ell n \left(\frac{a}{r_o}\right)\right) \frac{B_\theta^2}{8\pi} = -E\,(n_b eV_b - n_e eV_e) \tag{4}$$

where $\nu_{be(i)}$ is the beam-electron (ion) momentum exchange collision frequency and ν_{eq} is the electron-ion temperature equilibration collision frequency. Also τ_e is the electron energy confinement time, P_r is the free-free bremsstrahlung power loss and P_α is the α particle heating. (The α particle energy is assumed to be deposited directly in the electrons). The electron confinement time is taken to have the generally agreed[10] upon scaling with density and radius, namely $\tau_e = 1.5 \times 10^{-18}\, n_e r_o^2$, where the numerical factor is taken to agree with recent PLT experiments.[11] Also $\tau_i = {r_o^2}/{2K_{ci}}$ where K_{ci} is the neoclassical ion thermal conduction taken from Rutherford and Düchs,[12] r_o is the plasma (and beam) radius and a is the limiter radius. These equations are supplemented by equations for electric field

$$E = -\frac{m\nu}{e} V_e - \frac{n_b M \nu_b}{n_e} (V_e - V_b) \tag{5}$$

and electron drift velocity

$$V_e = -\frac{cB_\theta}{2\pi r_o n_e e} + \frac{n_b}{n_o} V_b, \quad (6) \tag{6}$$

where ν is the classical electron-ion collision frequency. These equations can be shown to conserve total energy and will be discussed more fully elsewhere.

Numerical solutions are shown in Fig. (1a-c) for plasmas characteristic of versator, PLT and Alcator C (or ignitor). In all cases, the beam current is the total current and $Z_{ef} = 1$. For versator the initial electron and ion temperatures are 100 ev and 50 ev; otherwise they are 1 keV and 500 ev. The beam currents and toroidal magnetic fields are always chosen so that $q > 1$. For versator it is a proton beam into a hydrogen plasma, for ignitor a tritium beam into a DT plasma, while for PLT both cases are shown. Finally let us reemphasize that after $t = 0$ at beam injection, there is no external energy input into the plasma.

Figure 1a is shown the electron and ion temperature, beam velocity and total current as a function of time for versator, with $B = 10$ KG, $n_e = 10^{13}$ cm^{-3}, $r_o = 15$ cm, $a = 30$ cm and $R = 45$ cm. The beam voltage and current are 3×10^5V and 6×10^4A. Assuming the pulse duration is the same for the beam ion to go around the torus, the time and total energy are $\tau = 3 \times 10^{-7}$ sec, $E = 6 \times 10^3$ Joules.

Notice that the decay time for the total current is greater than the decay time for the beam. The reason is that as the beam decays, it sets up a return current in the plasma. Because the plasma is heated significantly by the beam, its conductivity and L/R decay time thereby increase, so that the decay time of the plasma is much larger than the decay time of the beam. It is interesting to note that even though the beam gives forward momentum to the plasma electrons, they end up going backwards. The reason of course is that the total field cannot abruptly change sign because of the inductance of the system.

In Fig. 1b, the time dependence of the electron and ion temperature shown for PLT with a proton beam in a hydrogen plasma. Here r_o = 20 cm, a = 40 cm, R = 140 cm, $n_o = 10^{14}$ cm^{-3}, B = 40 KG and the beam voltage and current are 2.1 MeV and 500 KA. Figure 1b shows that a tritium beam does not heat a DT plasma as well. Defining Q as the energy of the reaction products (from both beam-plasma and plasma-plasma reactions) divided by the sum of the initial beam plus plasma plus poloidal field energy, we find Q = 0.1 for Fig. 1b. This could be nearly doubled for a T beam into a D plasma.

Finally in Fig. 1c is shown a result for ignitor. Here r_o = 10 cm, a = 20 cm, R = 60 cm, n = 10^{15} cm^{-3} and B = 160 KG. It is a 5 Megavolt, 1.5 Megamp 200 nanosecond (or four 50 nanosecond beams) tritium beam (E = 1.5 Megajoules) shot into a D.T. plasma. The plasma ignites, and after the numerical integration stops at t = 1 seconds, Q > 12. This high field-high density plasma ignites because of the high power density and high confinement time, as discussed by Coppi.[13]

The beam heating approach has several advantages over Ohmic heating. Chiefly there is the enormous power of the beam. The 1.5 megajoules of beam energy is deposited in about 100 milliseconds representing an initial power dissipation of 15 Megawatts. Secondly, before the beam slows down, it deposits the last bit of its energy into the ions. In this case, it leads to an ion temperature increase of about 2 Kev and this final boost leads directly to ignition.

To summarize, the transient tokamak seems to have great potential for both interesting physics experiments and economical experimental designs. It also seems to have very promising reactor possibilities. Particularly intriguing is the idea that one shot from an external source can supply all of the energy and current to ignite a plasma in a tokamak.

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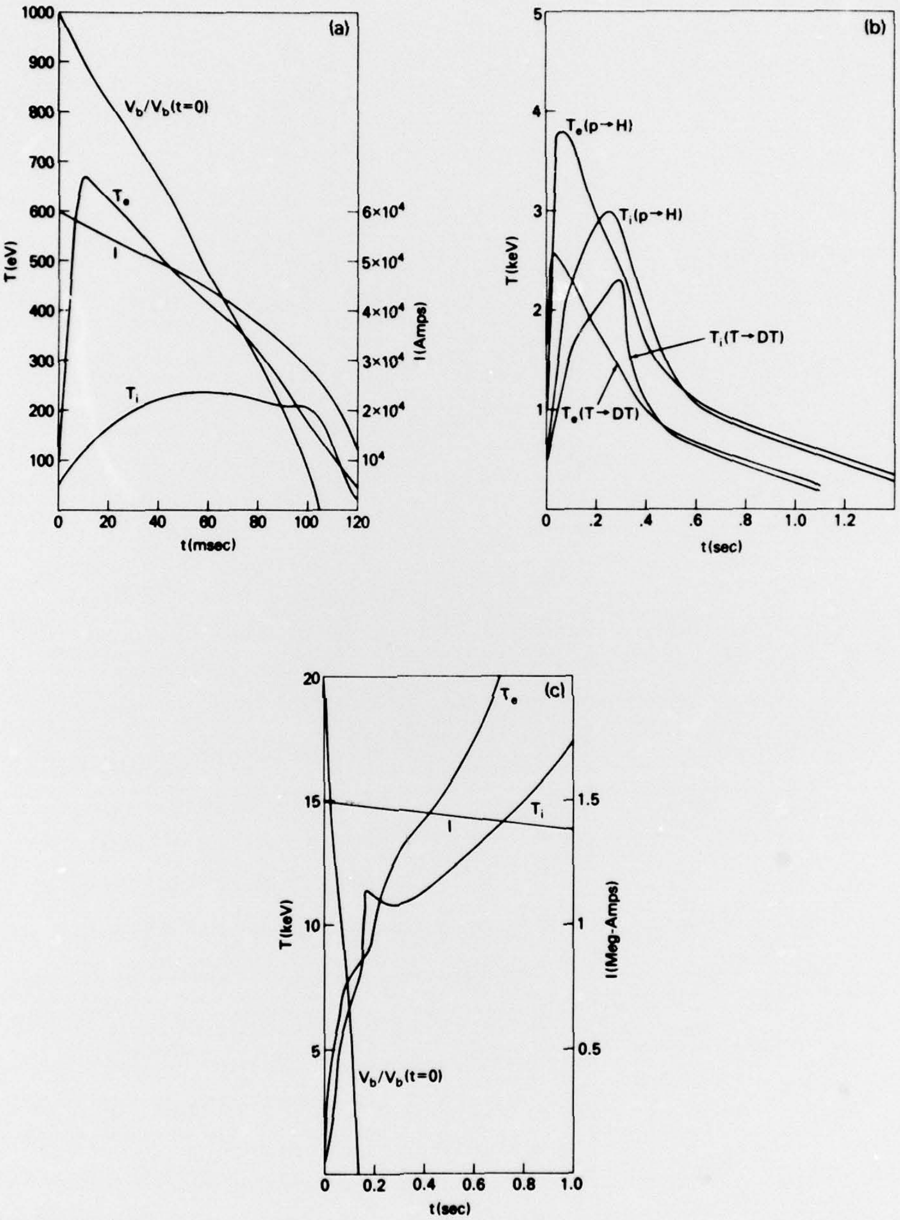

Fig. 1 - A plot of time dependence of a) T_e, T_i, I and normalized beam velocity for versator, b) T_e and T_i for PLT for the two case of a proton beam into a hydrogen plasma and Deuteron beam into a DT plasma, and c) like 1a for Alacator C.